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HIGH-ORDER MODELING OF AN ERL FOR ELECTRON COOLNG IN THE RHIC LUMINOSITY UPGRADE USING MARYLIE/IMPACT*

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Abstract

Plans for the RHIC luminosity upgrade call for an electron cooling system that will place substantial demands on the energy, current, brightness, and beam quality of the electron beam. In particular, the requirements demand a new level of fidelity in beam dynamics simulations. New developments in MARYLIE/IMPACT have improved both the space-charge computations for beams with large aspect ratios and the beam dynamic computations for rf cavities. We present the results of beam dynamics simulations that include the effects of space charge and nonlinearities, and aim to assess the tolerance for errors and nonlinearities on current designs for a super-conducting ERL.

INTRODUCTION

An electron cooling section has been proposed as part of a luminosity upgrade for RHIC [1]. This electron cooling section will be different from previous electron cooling facilities in three fundamental ways. First, the electron energy will be 50 MeV, as opposed to 100s of keV (or 4 MeV for the electron cooling system now operating at Fermilab [3]). Second, both the electron beam and the ion beam will be bunched, rather than being essentially continuous. Third, the cooling will take place in a collider rather than in a storage ring.

The design challenges of the RHIC e-cooling line require the development of simulation software capable of modeling both higher-order effects of the beam-line elements and 3D space charge effects. MARYLIE/IMPACT (ML/I) is currently being upgraded to meet these challenges. ML/I is a 3D parallel particle-in-cell code that combines the nonlinear optics capabilities of MARYLIE 5.0 with the parallel particle-in-cell space-charge capability of IMPACT. In addition to combining the capabilities of these codes, ML/I has a number of powerful features, including a choice of Poisson solvers, a fifth-order rf cavity model, multiple reference particles for rf cavities, a library of soft-edge magnet models, representation of magnet systems in terms of coil stacks with possibly overlapping fields, and wakefield effects. The code allows for map production, map analysis, particle tracking, and 3D envelope tracking, all within a single, coherent user environment.

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UPGRADES TO MARYLIE/IMPACT

During the past year several improvements to the ML/I code have been added in order to allow effective studies of the RHIC ecooling linac beam-line. These include the addition of a 3D integrated Greens function (IGF) poisson solver and its parallization. This was added to handle the large aspect ratios of the beams used in the e-cooling linac. Also added was the ability to handle random misalignments in a given beam-line. These were applied using the dynamical Euclidean group of E. Forest [4, 5]. The solenoid element was also upgraded to allow element slicing in order to permit the correct application of space charge kicks.

3D Integrated Greens Function

For high-aspect-ratio beams, accurate computation of space-charge forces is challenging. The standard discretization of the convolution integral

$$\phi(\vec{r}) = \int \rho(\vec{r})G(\vec{r}-\vec{r}')d\vec{r}' \tag{1}$$

requires that the product ρG vary slowly over a cell; but for large aspect ratios, G can vary much more rapidly than ρ. The integrated Greens function (IGF) technique replaces $\rho(\vec{r})$ with a linear approximation, and the G that appears in the discretized convolution sum becomes an effective Greens function, G^{eff}, obtained by integrating the appropriate Greens function with linear basis functions; hence

$$\phi_{ijk} \approx \sum \rho_{i'j'k'} G^{\mathrm{eff}}_{i-i',j-j',k-k'}. \tag{2}$$

This approach has been very successful in 2D. In 3D, it has been implemented using constant basis functions, but never before with linear basis functions.

The integrals required in the computation of G^{eff} are complicated and require quad precision arithmetic. As a consequence, the 3D IGF calculation of space-charge for large-aspect-ratio beams demands considerable computational effort. To speed these computations, we parallelized the calculation of the IGFs over the domain grid, and we recompute the IGF array only when the change in the bunch size is sufficient to require it. These changes sped up the IGF calculations by a factor of 10 with 16 processors.

Application of the Dynamical Euclidean Group

Following E. Forest's treatment of the dynamical Euclidean group [4], we have modified MARYLIE/IMPACT to include the effects of misaligned beam-line elements on particle trajectories. We applied the method outlined to treat beam-line elements with bend angles less than 180 degrees. In this approach the element is first made thin, then misaligments are treated by translating the particle coordinates at the entrance and exit of the thin element, and then the element is made "unthin". The construction of the misaligned element map can be characterized as follows,

$$\mathcal{M}_{\text{thin}}(\theta) = \mathcal{D}\left(\frac{-L}{2}\right)\mathcal{Y}\left(\frac{-\theta}{2}\right)\mathcal{M}\mathcal{Y}\left(\frac{-\theta}{2}\right)\mathcal{D}\left(\frac{-L}{2}\right),$$
$$\mathcal{M}_E(\theta) = \mathcal{Y}\left(\frac{\theta}{2}\right)\mathcal{D}\left(\frac{L}{2}\right)\mathcal{E}\mathcal{M}_{\text{thin}}\mathcal{E}^{-1}\mathcal{D}\left(\frac{L}{2}\right)\mathcal{Y}\left(\frac{\theta}{2}\right).$$

Here $\mathcal{M}_E$ is the final map—with misalignments—and $\mathcal{M}$ is the original transfer map for the beam-line element. The angle θ denotes the angle between the entrance and exit planes of the element, $\mathcal{D}(L/2)$ is a drift of half the element length, and $\mathcal{E}$ describes the misalignment of the element. In particular,

$$\mathcal{E} = \mathcal{T}(\vec{d})\mathcal{X}(\theta_x)\mathcal{Y}(\theta_y)\mathcal{Z}(\theta_z), \quad (3)$$

where $\mathcal{T}(\vec{d})$ describes the translational part of the misalignment, and $\mathcal{X}(\theta_x)\mathcal{Y}(\theta_y)\mathcal{Z}(\theta_z)$ describes the rotational part of the misalignment.

PRELIMINARY TRACKING RESULTS

We used ML/I to track through a proposed e-cooling beam-line [2] and compared our results against Parmela with and without space-charge effects turned on. We also applied random misalignments to the bending elements of the beam-line.

Comparison with Parmela

Comparisons with Parmela tracking without space charge are shown in Fig. 1. Slight differences do exist, and these can be attributed to the use in ML/I of realistic models (including extended fringe fields) for solenoids and higher-order tracking for bending elements. Parmela uses a hard-edge solenoid as defined in TRANSPORT [6], and it uses second-order tracking through bending magnets. Tracking with space-charge shows more pronounced differences between Parmela and ML/I (see Fig. 2), but the overall structure and size remain similar.

Effect of Bending Magnet Misalignments

We applied random transverse misalignments of 0.5mm and 5mm rms to the bending magnets in the beam-line (see Figs. 3–4). The 5mm case is, for our purposes, artificially large, but it serves to illustrate that there is no inherent difficulty with tracking in the presence of large misalignments. The effect of these misalignments seems confined to the plane in which they were applied. This reflects the weakness of the coupling induced by the solenoids. As well the impact appears more pronounced in the horizontal plane than in the vertical. We also applied random tilt errors of

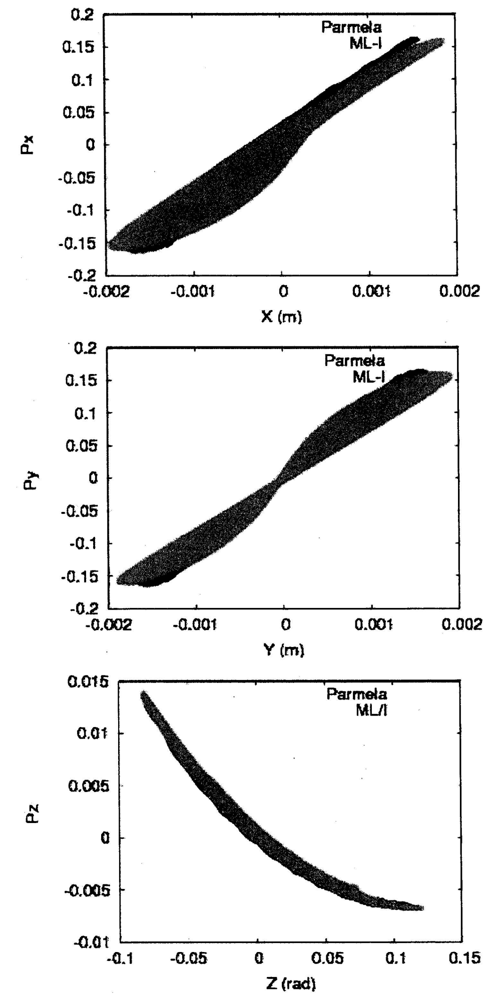

Figure 1: Phase space plots of tracking through a proposed RHIC e-cooling linac, without space charge (ML/I in green, and Parmela in red). The plots show horizontal (top), vertical (middle), and longitudinal (bottom) phase space projections.

0.5 degrees rms around the longitudinal axis (see Fig. 5). This affected both planes, but, again, the effect was more pronounced in the horizontal. Overall the rotational errors seemed to be the most destructive to the emittance size.

CONCLUSION

Initial results from tracking with ML/I through a proposed ERL beam-line indicates a strong sensitivity to bend magnet rolls, with less sensitivity to transverse misalignments. We are currently considering the sensitivity of another optized beam-line. In addition, we plan to perform sensitivity tests for misalignments for other beam-line elements.

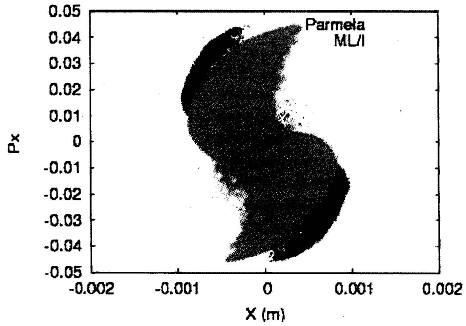

Figure 2: Horizontal phase space of a proposed RHIC e-cooling linac, with space charge (ML/I in green, and Parmela in red).

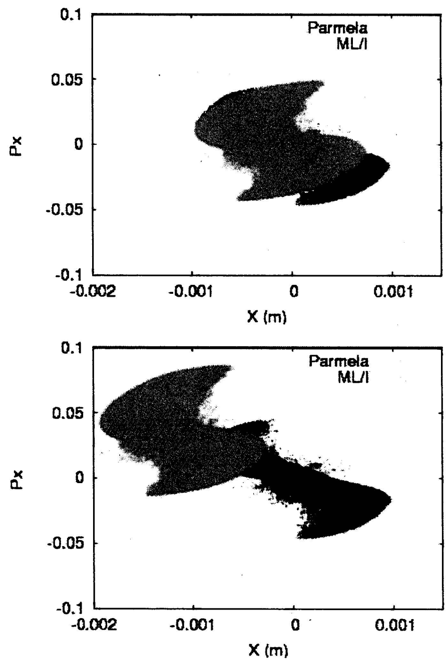

Figure 3: Horizontal phase space plots of a proposed RHIC e-cooling linac, with space charge. Horizontal random misalignments of bending elements of 0.5 mm (top) and 5.0 mm rms (bottom). (ML/I in green, and Parmela in red.)

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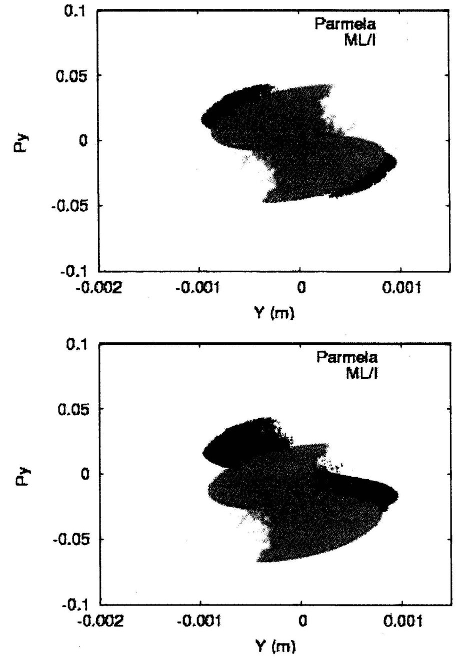

Figure 4: Vertical phase space plots of a proposed RHIC e-cooling linac, with space charge. Vertical random misalignments of bending elements of 0.5 mm (top) and 5.0 mm rms (bottom). (ML/I in green, and Parmela in red.)

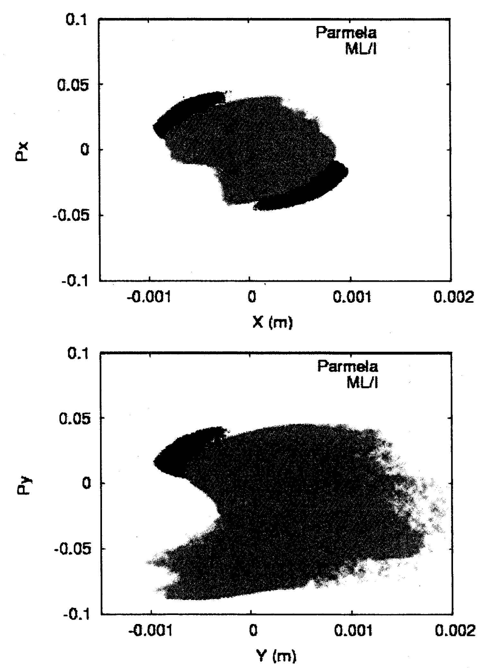

Figure 5: Horizontal (top) and vertical (bottom) phase space plots of a proposed RHIC e-cooling linac, with space charge and random rotations of bending elements of 0.5 degrees rms. (ML/I in green, and Parmela in red.)